CP Violation in the SM and Beyond in Hadronic B Decays

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Abstract

Three different methods, using $B_d \to J/\psi K_S,\ J/\psi K_S\pi^0$, $B_d \to K^-\pi^+, \pi^+\pi^-$ and $B_u \to K^-\pi^0, \bar K^0\pi^-, \pi^-\pi^0$, to extract hadronic model independent information about new physics are discussed in this talk.

1. Introduction

In this talk I discuss three methods, using $B_d \to J/\psi K_S,\ J/\psi K_S\pi^0$ [1], $B_d \to K^-\pi^+, \pi^+\pi^-$ [2] and $B_u \to K^-\pi^0, \bar K^0\pi^-, \pi^-\pi^0$ [3,4], to extract hadronic model independent information about the SM and models beyond.

The SM effective Hamiltonian respossible for hadronic decays is known-Ref. [5]. When going beyond the SM, there are new contributions. I will take three models beyond the SM for illustrations.

Model i): R-parity violation model

In R-parity violating supersymmetric (SUSY) models, there are new CP violating phases. Here I consider the effects due to, $L = (\lambda''_{ijk}/2)U^{ci}_R D^{cj}_R D^{ck}_R$, R-parity violating interaction. Exchange of $\tilde d_i$ squark can generate the following effective Hamiltonian at tree level, $H_{eff} = (4G_F/\sqrt{2})\ V^*_{fb}V_{fq}\ c^{f(q)}[O^{f(q)}_1(R) - O^{f(q)}_2(R)]$. Here $O^{f(q)}_1(R) = \bar f\gamma_\mu R f\bar q\gamma^\mu R b$ and $O^{f(q)}_2(R) = \bar f_\alpha\gamma_\mu R f_\beta \bar q_\beta\gamma^\mu R b_\alpha$. The operators $O_{1,2}(R)$ have the opposite chirality as those of the tree operators $O_{1,2}(L)$ in the SM. The coefficients $c^{f(q)}$ with QCD corrections are given by $(c_1 - c_2)(\sqrt{2}/(4G_F V_{fb}V^*_{fq}))(-\lambda''_{fqi}\lambda''^*_{f3i}/2m^2_{\tilde d^i})$. Here $m_{\tilde d^i}$ is the squark mass. $B_u \to \pi^-\bar K^0$ and $B_u \to K^-\bar K^0$ data constrain $|c^{c(q)}|$ to be less than $O(1)$ [6]. The new contributions can be larger than the SM ones. I will take the values to be 10% of the corresponding values for the SM with arbitrary phases $\delta^{f(q)}$ for later discussions.

Model ii): SUSY with large gluonic dipole interaction

In SUSY models with R-parity conservation, potential large contributions to B decays may come from gluonic dipole interaction c^{new}_{11} by exchanging gluino at loop level with left- and right-handed squark mixing. c^{new}_{11} is constrained by experimental data from $b \to s\gamma$ which, however, still allows c^{new}_{11}

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to be as large as three times of the SM contribution in magnitude with an arbitrary CP violating phase δ_{dipole} [7]. I will take c_{11}^{new} to be 3 times of the SM value with an arbitrary δ_{dipole}.

Model iii): Anomalous gauge boson couplings

Anomalous gauge boson couplings can modify the Wilson Coefficients of the SM ones with the same CP violating source as that for the SM [4,8]. The largest contribution may come from the WWZ anomalous coupling Δg_1^Z. LEP data constrain [9] Δg_1^Z to be within $-0.113 < \Delta g_1^Z < 0.126$ at the 95% c.l.. The resulting Wilson Coefficients can be very different from those in the SM.

2. Test new physics and $\sin 2\beta$ from $B \to J/\psi K_S, J/\psi K_S \pi^0$

The usual CP violation measure for B decays to CP eigenstates is $\mathrm{Im}\,\xi = \mathrm{Im}\,\{(q/p)(A^*\bar{A}/|A|^2)\}$, where $q/p = e^{-2i\phi_B}$ is from B^0–$\bar{B}^0$ mixing, while A, $\bar{A}$ are B, $\bar{B}$ decay amplitudes. For $B \to J/\psi K_S$, the final state is P-wave hence CP odd. Setting the weak phase in the decay amplitude to be $2\phi_0 = Arg(A/\bar{A})$, one has , $\mathrm{Im}\,\xi(B \to J/\psi K_S) = -\sin(2\phi_B + 2\phi_0) \equiv -\sin 2\beta_{J/\psi K_S}$.

For $B \to J/\psi K^* \to J/\psi K_S \pi^0$, the final state has both P-wave (CP odd) and S- and D-wave (CP even) components. If S- and D-wave have a common weak phase $\tilde{\phi}_1$ and P-wave has a weak phase ϕ_1 [1],

$$\begin{aligned}\mathrm{Im}\,\xi(B \to J/\psi K_S \pi^0) &= \mathrm{Im}\,\{e^{-2i\phi_B}[e^{-2i\phi_1}|P|^2 - e^{-2i\tilde{\phi}_1}(1-|P|^2)]\}\\ &\equiv (1-2|P|^2)\sin 2\beta_{J/\psi K_S\pi^0}, \qquad (1)\end{aligned}$$

where $|P|^2$ is the fraction of P-wave component. In the SM one has $\phi_B = \beta$ and $2\phi_0 = 2\phi_1(2\tilde{\phi}_1) = Arg[\{V_{cb}V_{cs}^*\{c_1 + a(a')c_2\}\}/\{V_{cb}^*V_{cs}\{c_1 + a(a')c_2\}\}] = 0$, in the Wolfenstein phase convention. Here a and a' are parameters which indicate the relative contribution from $O_2^{c(s)}(L)$ compared with $O_1^{c(s)}(L)$ for the P-wave and (S-, D-) wave. In the factorization approximation $1/a = 1/a' = N_c$ (the number of colors). Therefore $\sin 2\beta_{J/\psi K_S} = \sin 2\beta_{J/\psi K_S\pi^0} = \sin 2\beta$. $|P|^2$ has been measured with a small value [10] $0.16 \pm 0.08 \pm 0.04$ by CLEO which implies that the measurement of $\sin 2\beta$ using $B \to J/\psi K_S \pi^0$ is practical although there is a dilution factor of 30%.

When one goes beyond the SM, $\sin 2\beta_{J/\psi K_S} = \sin 2\beta_{J/\psi K_S\pi^0}$ is not necessarily true. Let us now analyze the possible values for $\Delta \sin 2\beta \equiv \sin 2\beta_{J/\psi K_S} - \sin 2\beta_{J/\psi K_S\pi^0}$. Because $B \to J/\psi K_S, J/\psi K^*$ are tree dominated processes, Models ii) and iii) would not change the SM predictions significantly. $\Delta \sin 2\beta$ is not sensitive to new physics in Models ii) and iii). However, for Model i), the contributions can be large. The weak phases are given by $2\phi_0 = 2\phi_1(2\tilde{\phi}_1) = Arg[\{V_{cb}V_{cs}^*\{c_1 + ac_2 + (-)c^{c(s)}\{1 - a(a')\}\}\}/\{V_{cb}^*V_{cs}\{c_1 + ac_2 +$

$(-)c^{c(s)*}\{1-a(a')\}\}\}]$. Taking the new contributions to be 10% of the SM ones, one obtains $\phi_0 = \phi_1 \approx -\tilde{\phi}_1 \approx 0.1\sin\delta^{c(s)}$. From this, $\Delta\sin 2\beta \approx 4((1-|P|^2)/(1-2|P|^2))\cos 2\phi_B(0.1\sin\delta^{c(s)}) \approx 0.5\cos 2\phi_B \sin\delta^{c(s)}$. ϕ_B may be different from the SM one due to new contributions. Using the central value $\sin 2\beta_{J/\psi K_S} = 0.91$ measured from CDF and ALEPH[11], $\Delta\sin 2\beta \approx 0.2\sin\delta^{c(s)}$ which can be as large as 0.2. Such a large difference can be measured at B factories. Information about new CP violating phase $\delta^{c(s)}$ can be obtained.

3. Test new physics and rate differences between $B_d \to \pi^+ K^-, \pi^+\pi^-$

I now show that hadronic model independent information about CP violation can be obtained using SU(3) analysis for rare hadronic B decays.

The SM operators $O_{1,2}$, $O_{3-6,11,12}$, and O_{7-10} for rare hadronic B decays transform under SU(3) symmetry as $\bar{3}_a + \bar{3}_b + 6 + \overline{15}$, $\bar{3}$, and $\bar{3}_a + \bar{3}_b + 6 + \overline{15}$, respectively. These properties enable one to write the decay amplitudes for $B \to PP$ in only a few SU(3) invariant amplitudes. When small annihilation contributions are neglected, one has

$$\begin{aligned} A(B_d \to \pi^+\pi^-) &= V_{ub}V_{ud}^* T + V_{tb}V_{td}^* P, \\ A(B_d \to \pi^+ K^-) &= V_{ub}V_{us}^* T + V_{tb}V_{ts}^* P. \end{aligned}$$

From above one obtains, $\Delta(\pi^+\pi^-) = -\Delta(\pi^+K^-)$. This non-trivial equality dose not depend on detailed models for hadronic physics and provides test for the SM[2]. Including SU(3) breaking effect from factorization calculation, one has, $\Delta(\pi^+\pi^-) \approx -\frac{f_\pi^2}{f_K^2}\Delta(\pi^+K^-)$. Although there is correction, the relative sign is not changed.

When going beyond the SM, there are new CP violating phases leading to violation of the equality above. For example Models i) and ii) can alter the equality significantly, while Model iii) can not because the CP violating source is the same as that in the SM. To illustrate how the situation is changed in Models i) and ii), I calculate the normalized asymmetry $A_{norm}(PP) = \Delta(PP)/\Gamma(\pi^+K^-)$ using factorization approximation following Ref. [12]. The new effects may come in such a way that only $B_d \to \pi^+K^-$ is changed but not $B_d \to \pi^+\pi^-$. This scenario leads to maximal violation of the equality discussed here.

The results are shown in Figure 1. The solid curve is the SM prediction for $A_{norm}(\pi^+K^-)$ as a function of γ. For γ_{best} $A_{norm}(\pi^+K^0) \approx 10\%$. It is clear from Figure 1 that within the allowed range of the parameters, new physics effects can dramatically violate the equality discussed above.

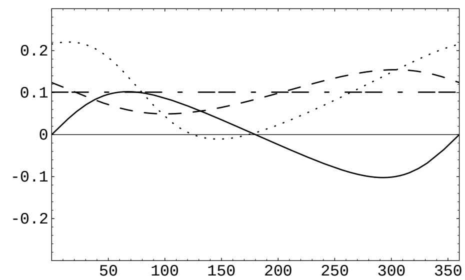

Figure 1: $A_{norm}(\pi^+K^-)$ vs. phases γ, $\delta^{u(s)}$ and δ_{dipole} for the SM (solid), Models i) (dashed) and ii) (dotted). For Models i) and ii), $\gamma = 59.9^\circ$ is used. $A_{norm}(\pi^+K^-) = -(f_\pi/f_k)^2 A_{norm}(\pi^+\pi^-)$ is satisfied in the SM. For Models i) and ii) $-(f_\pi/f_k)^2 A_{norm}(\pi^+\pi^-)$ is approximately the same as that in the SM (dot-dashed curve).

4. Test new physics and SU(3) relation for $B_u \to \pi^-\bar{K}^0, \pi^0 K^-, \pi^0\pi^-$

I now discuss another method which provides important information about new physics using $B_u \to \pi^-\bar{K}^0, \pi^0 K^-, \pi^0\pi^-$. Using SU(3) relation and factorization estimate for the breaking effects, one obtains [3,4]

$$\begin{aligned} A(B_u \to \pi^-\bar{K}^0) + \sqrt{2}A(B_u \to \pi^0 K^-) &= \epsilon A(B_u \to \pi^-\bar{K}^0) e^{i\Delta\phi}(e^{-i\gamma} - \delta_{EW}), \\ \delta_{EW} = -\frac{3}{2}\frac{|V_{cb}||V_{cs}|}{|V_{ub}||V_{us}|}\frac{c_9 + c_{10}}{c_1 + c_2}, & \qquad \epsilon = \sqrt{2}\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi}\frac{|A(\pi^+\pi^0)|}{|A(\pi^+K^0)|}, \end{aligned}$$

where $\Delta\phi$ is the difference of the final state rescattering phases for $I = 3/2, 1/2$ amplitudes. For $f_K/f_\pi = 1.22$ and $Br(B^\pm \to \pi^\pm\pi^0) = (0.54^{+0.21}_{-0.20} \pm 0.15) \times 10^{-5}$ [13], one obtains $\epsilon = 0.21 \pm 0.06$.

Neglecting small tree contribution to $B_u \to \pi^-\bar{K}^0$, one obtains

$$\cos\gamma = \delta_{EW} - \frac{(r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2)}{2\epsilon(\cos\Delta\phi + \epsilon\delta_{EW})}, \quad r_+^2 - r_-^2 = 4\epsilon\sin\Delta\phi\sin\gamma,$$

where $r_\pm^2 = 4Br(\pi^0 K^\pm)/[Br(\pi^+K^0) + Br(\pi^-\bar{K}^0)] = 1.33 \pm 0.45$ [13].

It is interesting to note that although the above equation is complicated, bound on $\cos\gamma$ can be obtained [4]. For $\Delta = (r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2) \geq (\leq) > 0$, we have

$$\cos\gamma \leq (\geq)\delta_{EW} - \frac{\Delta}{2\epsilon(1 + \epsilon\delta_{EW})}, \quad \text{or} \quad \cos\gamma \geq (\leq)\delta_{EW} - \frac{\Delta}{2\epsilon(-1 + \epsilon\delta_{EW})}. \quad (2)$$

The bounds on $\cos\gamma$ as a function of δ_{EW} are shown in Fig. 2 by the solid curves for three representative cases: a) Central values for ϵ and $r^2_\pm$; b) Central values for ϵ and 1σ upper bound $r^2_\pm = 1.78$; and c) Central value for ϵ and 1σ lower bound $r^2_\pm = 0.88$. The bounds with $|\cos\gamma| \leq 1$ for a), b) and c) are indicated by the curves (a1, a2), (b) and (c1, c2), respectively. For cases a) and c) there are two allowed regions, the regions below (a1, c1) and the regions above (a2, c2). For case b) the allowed range is below (b).

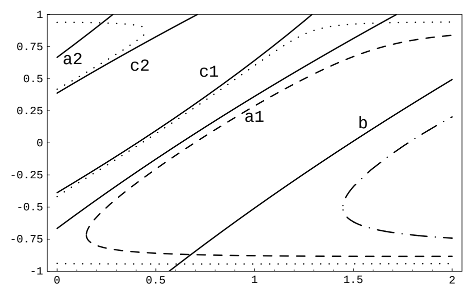

Figure 2: $\cos\gamma$ vs. δ_{EW}. The solutions for the cases a), b) and c) are indicated by the dashed, dot-dashed and dotted curves respectively.

One also has

$$(1-\cos^2\gamma)[1-(\frac{\Delta}{2\epsilon(\delta_{EW}-\cos\gamma)}-\epsilon\delta_{EW})^2]-\frac{(r_+^2-r_-^2)^2}{16\epsilon^2}=0. \qquad (3)$$

To have some idea about the details, I analyze the solutions of $\cos\gamma$ as a function of δ_{EW} for the three cases discussed earlier with a given value for the asymmetry $A_{asy} = (r_+^2 - r_-^2)/(r_+^2 + r_-^2) = 15\%$.

In the SM for $r_v = |V_{ub}|/|V_{cb}| = 0.08$ and $|V_{us}| = 0.2196$, $\delta_{EW} = 0.81$. The central values for $r_\pm$ and ϵ prefers $\cos\gamma < 0$ which is different from the result obtained in Ref. [14] by fitting other data. The parameter δ_{EW} is sensitive to new physics in the tree and electroweak sectors. Model i) has large corrections to the tree level contributions. However, the contribution is proportional to the sum of the coefficients of operators $O^{u(s)}_{1,2}(R)$ which is zero in Model i). The above method does not provide information about new physics due to Model i). This method would not provide information about new physics due to Model ii) neither because the gluonic dipole interaction transforms as $\bar{3}$ which does not affect δ_{EW}. Model iii) can have large effect on δ_{EW}. In this model $\delta_{EW} = 0.81(1+4.33\Delta g_1^Z)$ which can vary in the range $0.40 \sim 1.25$.

For case a), in the SM $\cos\gamma < 0.18$ which is inconsistent with $\cos\gamma_{best} \approx 0.5$ from other fit [14]. In Model iii) $\cos\gamma$ can be consistent with $\cos\gamma_{best}$. For case

b), $\cos\gamma$ is less than zero in both the SM and Model iii). If this is indeed the case, other types of new physics is needed. For case c) $\cos\gamma$ can be close to $\cos\gamma_{best}$ for both the SM and Model iii).

5. Conclusion

From discussions in previous sections, it is clear that using $B_d \to J/\psi K_S$, $J/\psi K_S \pi^0$, $B_u \to \pi^- K^+, \pi^+\pi^-$ and $B^- \to \pi^0 K^-, \pi^- \bar{K}^0, \pi^0\pi^-$ important information free from uncertainties in hadronic physics about the Standard Model and models beyond can be obtained. These analyses should be carried out at B factories.

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